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STUDY OF EXTRATERRESTRIAL DISPOSAL OF RADIOACTIVE WASTES

Part III - Preliminary Feasibility Screening Study of Space Disposal of the Actinide Radioactive Wastes with 1 Percent and 0.1 Percent Fission Product Contamination

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ABSTRACT

A preliminary study was conducted of the feasibility of space disposal of the actinide class of radioactive waste material. This waste was assumed to contain 1 and 0.1 percent residual fission products, since it may not be feasible to completely separate the actinides. The actinides are a small fraction of the total waste but they remain radioactive much longer than the other wastes and must be isolated from human encounter for tens of thousands of years. Results indicate that space disposal is promising but more study is required, particularly in the area of safety. The minimum cost of space transportation would increase the consumer electric utility bill by the order of 1 percent for earth escape and 3 percent for solar escape. The waste package in this phase of the study was designed for normal operating conditions only; the design of next phase of the study will include provisions for accident safety. The number of Shuttle launches per year required to dispose of all U.S. generated actinide waste with 0.1 percent residual fission products vary between 3 and 15 in 1985 and between 25 and 110 by 2000. The lower values assume Earth escape (solar orbit) and the higher values are for escape from the solar system.

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STUDY OF EXTRATERRESTRIAL DISPOSAL

OF RADIOACTIVE WASTES

Part III

Preliminary Feasibility Screening Study of Space Disposal of the Actinide Radioactive Wastes with 1 Percent and 0.1 Percent Fission Product Contamination

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1. INTRODUCTION

The NASA has been requested by the AEC to study the feasibility of extraterrestrial or space disposal of radioactive waste generated in U.S. nuclear stationary powerplants. Disposal in space has been considered as one of several possibilities for disposal or storage of radioactive waste (ref. 1). This report is one part of a series that are being issued on "Extraterrestrial Disposal of Radioactive Waste." Reference 2 (Part I) considered the launch vehicles that could be used and the various destinations that could be considered. Reference 3 (Part II of the series) considered the disposal of one type of radioactive waste, namely all of the fission products remaining in the waste material after reprocessing all spent nuclear fuel and storing it for 10 years or more. The fission products were assumed to be solidified into a durable matrix material and sealed in shielded cylinders similar to those proposed for Earth storage. The analysis considered normal operations only. It was concluded that the space transportation cost for Earth escape would add only a few percent to the consumer electric cost, assuming the waste was stored on Earth for several decades prior to launch. The number of Shuttle launches required would be greater than one per day within five years after the start of a launch program.

This report considers a second type of radioactive waste material, namely the actinides which are not fission products. They are formed by transmutations occurring when neutrons, protons or heavy particles are added to the nucleus of high mass atoms such as uranium and plutonium. These elements have higher atomic numbers than actinium and hence are called actinides. The actinides are radioactive. They are especially hazardous because of their very long half lives (some greater than 20 000 years). The purpose of this preliminary study was to determine whether or not space disposal could be practical from the standpoint of launch frequency and cost of transportation. In separating the actinides from the useable fuel and the fission products in spent reactor fuel some

fission product contamination remains. In this report we assume that 1 and 0.1 percent of the fission products remains in the actinide waste. In addition it was assumed that all of the uranium isotopes were removed. This preliminary report, like reference 3, analyzes space disposal considering only normal operations. The penalty imposed by accident safety considerations will be determined in the next phase of this study. The design for normal operation provides for cooling of the waste material, radiation shielding, and prevention of nuclear criticality. The next phase of the study will consider all safety aspects, such as launch pad accidents, uncontrolled reentry, land impact, and package burial. W. Ward Engle and R. L. Childs of the Oak Ridge National Laboratory contributed to the neutron and gamma-ray shielding weight optimization calculations performed on the SHAPE code.

2. DESCRIPTION OF WASTE PRODUCTS, MATRIX MATERIALS, AND CONTAINERS

2.1 Description of Waste Products

The radioactive wastes selected for this study are the actinide elements with small percentages of fission products remaining from the separation processes. For this report two levels of fission products are assumed to remain in the waste. These are 1 percent and 0.1 percent of the total fission product inventory 10 years after processing.

As previously indicated, the actinides are not fission products from splitting nuclei but are radioactive isotopes formed by neutron absorption in heavy isotope nuclei above the element actinium. Most of the radioactive decay modes of the actinides involve the emission of an alpha particle (helium nucleus) and spontaneous fissions which result in emission of neutrons. The alpha decays usually involve long half-lives (i.e., time for the radioactivity to decrease by half), some of them measured in tens of thousands of years. The half-lives of the various actinide elements present in the waste material are shown in table 2-1. As noted in the table, different percentages of the isotopes are found in the waste material depending on the type of reactor in which the fuel was originally utilized. Table 2-2 shows the radioactive waste yields from light-water moderated thermal reactors (LWR) and liquid metal fast-breeder reactors (LMFBR). The difference in yield per kilowatt hour is due to the higher efficiency of the liquid metal reactors. The total yields for each metric ton of fuel processed are essentially the same for all reactor types but the distribution of isotopes is different. As these radioactive isotopes decay, they produce heat. Table 2-3 shows the thermal and radioactive characteristics of the actinides with and without fission products. The removal of the uranium isotopes creates a higher concentration of the radioactive isotopes and thus increases both thermal power and radioactivity.

The fission products remaining in the actinide waste after processing

will vary in type and amount depending on the capability of the reprocessing plant. For this study fission product contamination of 1 and 1/10 percent of the fission products was assumed to remain in the actinides. This would represent a weight fraction of fission products in the actinide mix of 0.20 and 0.02, respectively. The effect on the thermal heat generated is to lower the number of watts per gram of the total mix because of the relatively rapid decay of the fission products during a 10-year hold. This can be seen in the results tabulated in table 2-3. The radiation level in curies per gram is higher when more residual fission products remain in the actinide waste.

The actinides have high radiation levels and long half-lives. Since the permissible amount of radiation to the body is very low (ref. 5), the actinides must be disposed of or stored in such a way that there is no conceivable chance for human encounter for a period of time approaching a million years.

2.2 Description of Matrix Material for Actinide Waste

Because the actinides with fission products produce heat and consist of fissionable isotopes such as plutonium, americium, and curium, they must be mixed with another material, called a matrix material, to dilute the actinides to both prevent criticality and provide conduction paths to remove heat. The actinides and the fission products are normally in the form of oxides which typically have low thermal conductivity. Consequently, a high thermal conductivity matrix material such as aluminum or copper is required. Some of the actinides are fissionable, consequently to prevent criticality, the matrix material must also be a moderating material with neutron absorption capability. One such material is lithium hydride.

A method has been suggested by personnel at Battelle Pacific Northwest Laboratories to use a metal matrix of Cu and/or Al, containing lithium hydride particles along with boron particles. This matrix would then be used to contain the actinides, provide a dilution effect to prevent criticality and provide thermal conduction paths for heat removal. The actinide oxides along with the fission products would be spherical in shape with voids for helium accumulation due to alpha decay. These spheres could be coated with tungsten (~0.005 in.) for temperature stability and with an outer layer of molybdenum disulfide for oxidation protection. Processes of this type for coating spherical particles have been developed in the nuclear fuel industry. This matrix arrangement is shown in figure 2-1.

A mixture of 50 percent lithium hydride with 25 percent aluminum and 25 percent copper by volume of matrix material yields a thermal conductivity (theoretical - ref. 6) of 17 Btu/(hr)-(ft)-(°F) compared to approximately 2 for actinide oxides. This proposed matrix would have the desired characteristics of high-temperature stability, high neutron attenuation capability, and good thermal conductivity. The precise physical properties

of this material would have to be determined by measurement of manufactured samples.

It was assumed that the maximum temperature of the matrix material must not exceed the melting point of the lithium hydride (930 K). The assumption used is similar to that in reference 3 where the center temperature (maximum pt.) of the matrix was kept 70 K below the melting point. Therefore, the size shall be constrained by the payload weight limitation or by the maximum center temperature of 860 K (1090° F).

2.3 Description of Radiation Shielding and Containment System

Inasmuch as the actinides generally decay by emitting alpha particles, which are easily stopped, little shielding is needed for actinide decay radioactivity. However, some of the isotopes spontaneously fission, giving off neutrons and gamma rays, and some of the fission products resulting from spontaneous fission are gamma ray emitters. Neutrons and gamm rays are highly penetrating forms of radiation and each requires a different shielding material. Some of the shielding is provided by the self shielding effect of the matrix material which consists of LiH and metals. Metals attenuate gamma rays and fast neutrons effectively while lithium hydride is a good neutron attenuator. It is necessary to have some additional shielding surrounding this matrix material due to the proximity of radioactive material to the outer layers (hence, little or no self shielding). In addition the emitted neutrons and gamma rays have high energies in the MeV range. The outer layers of shielding are, in radial outward order, tungsten and lithium hydride. The arrangement is shown in figure 2-2. The outer containment vessel of stainless steel 304 is included for secondary containment during normal operation. It also is the primary container in the event of an aborted mission where the package impacts the Earth and fractures the matrix and the individual particle containment is destroyed. Stainless steel vessels similar to the one proposed here have been shown to survive impacts to 1055 ft/sec without rupture (refs. 7 and 8). For this analysis a thickness of 1 inch was selected for the stainless steel shell. The radiation shielding effectivness of this shell was not accounted for in the shielding analysis. The overall shield weight determination is therefore conservative. Impact containment, as well as other safety problems such as reentry protection, launch pad accidents and other emergency and accident situations will be analyzed in the next phase of the study.

The shielding analysis was conducted with the help of personnel at the ORNL. The SHAPE code was used for analysis. The radiation shielding was optimized for minimum weight for a dose level of 1 rem/hr at 1 meter from the surface of the sphere. The size of the sphere is determined by the temperature limit of lithium hydride in the matrix material (860 K) or the space vehicle payload capability for each of the various space destinations. This is discussed in the following section.

3. PAYLOADS AND COSTS FOR CANDIDATE DESTINATIONS AND SPACE VEHICLES

Vehicles, payloads, and space transportation costs are discussed in detail in reference 2 and are summarized in reference 9. The summary discussion presented in reference 3 for disposal of fission products is directly applicable to the actinide waste package and is repeated here. This report also discusses the reasons for selecting the shuttle as the launch vehicle and Earth escape and solar escape as the potential destinations for this study.

The gross payload[1] and the space transportation cost for a given destination and space vehicle is not significantly affected by the type of radioactive waste because the payload is almost constant. However, significant differences in thermal power of the payloads could influence the payload weight somewhat because of a change in the in-shuttle heat removal system weight which would affect the payload capacity. This effect is assumed to be small and was neglected in this study.

The candidate destinations in order of decreasing delta-V are: direct solar impact, direct solar escape, solar impact via Jupiter, solar escape via Jupiter, solar orbit, solar orbit via Venus, solar orbit via Mars, Earth escape and Earth orbit. Only operational or planned launch vehicle systems are considered. The candidate expendable vehicles in order of decreasing payload capability are: Saturn V/Centaur, Saturn V, and Titan III E/Centaur. The only planned candidate reusable vehicle is the Space Shuttle combined with an expendable or reusable Space Tug. There are several options for using the Space Shuttle in combination with Space Tugs for payload injection into orbit. Two types of Shuttle launches are considered. One is a single Shuttle launch which carries both the payload and the tug into Earth orbit. The tug transports the payload from low Earth orbit to its final destination. The other requires two or more Shuttle launches. One Shuttle carries the payload or payload and tug. The other Shuttle or Shuttles carry one tug each. The payload and tug (or tugs) rendezvous and are assembled in low Earth orbit. The tugs may be either expendable or reusable.

Table 3-1 shows the payloads and costs for the candidate destinations and candidate launch vehicle and tug combinations. Direct solar impact is not a possible destination with current or planned vehicles. The table also shows that the Shuttle vehicle is the most economical launch system. The cost per kilogram of payload in the Shuttle was at least a factor of two lower than the best of the expendable vehicles, namely the Saturn V vehicle.

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[1] Gross payload is defined as the weight of the total waste container system including all shielding and protective structures permanently attached and delivered to the destination. Waste support systems remaining onboard the Shuttle must be deducted from the payloads obtained in reference 2.

The Shuttle was therefore selected as the launch vehicle (figs. 3-1 and 3-2). Earth escape[2] was selected as the destination for the base case in this study. The payload to high Earth orbit is about the same as for Earth escape so that results of one can be used as the performance of the other. A solar escape mission was considered because it involves a destination for which no impact in the solar system would occur. These destinations chosen are relatively arbitrary at this time and will be re-evaluated in later phases of the study if required.

The trajectory of the launch phase of the mission used to calculate the above payloads did not include a dog-leg. Dog-legged trajectories may be required to avoid potential impact on land if abort occurs during ascent. Dog-legging will require more fuel and, if the Shuttle is fully loaded, will result in a reduced payload. When dog-legging is considered, the payload weight for the single Shuttle launch case is less than that for the dual launch. In the single launch case with a dog-leg, the Shuttle carries both the tug and the radioactive waste payload and is fully loaded.Because more fuel is required the waste payload is less. In the dual case the tug-carrying Shuttle is fully loaded and does not require the use of a dog-leg. The waste-carrying Shuttle is, however, only partially loaded and there is capacity for extra fuel for the dog-leg without reducing the payload. In this case, for example, the waste gross payload is 14 100 kilograms (31 000) and the in-Shuttle structure weighs 1363 kilograms for a total of 15 447 kilograms. This is considerably less than the maximum allowable of 28 200 kilograms (62 000 lb). The gross payload is limited to 13 180 kilograms (29 000 lb) because this is the maximum weight the tug can put into Earth escape orbit. Thus, in the dual Shuttle launch mode, 13 650 kilograms (30 000 lb) of additional fuel could be carried in the Shuttle with the payload, which is adequate for the dog-leg maneuver. The second Shuttle carrying the Tug can be launched with a conventional trajectory which does not require dog-legging.

Cost comparisons were made using the cost of existing expendable and reusable vehicle designs and included cost for launch operation. If space disposal of wastes is seriously considered, then the development of an expendable or reusable vehicle designed for this application should be considered. Cost savings could result due to optimization of the launch system for this particular mission.

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[2]Earth escape is a solar orbit obtained by one burn from Earth orbit. The important characteristic of this orbit is that it eventually intersects the Earth's orbit and introduces the possibility of Earth impact. Solar orbit refers to orbits about the Sun which are either inside or outside the Earth orbit with negligible probability of impacting the Earth. Solar orbits require two burns; the second 3 to 6 months after the first.

4. ANALYSIS FOR THE ACTINIDE PHASE I STUDY

The scope of the phase I analysis for the actinide radioactive waste with 1 and 0.1 percent fission products is essentially the same as that for the study of fission product waste in the matrix material and container designed for Earth storage (ref. 3). The actinide container shape is spherical rather than cylindrical as considered for the total fission product case. Spherical geometry yields minimum shield weight for comparable external dose rate constraints.

The phase I analysis considers normal operating conditions only and has two main parts. First, determination of the maximum amount of radioactive waste that could be carried in the Shuttle-Orbiter-Tug vehicle. Second, calculation of the launch cost per mission, per pound of waste, and per kilowatt-hour electric to establish the effect of launch cost on the electric generating cost. The number of launches required per year from 1985 through 2000 are also estimated.

If the effect on electric generating cost makes the system potentially unfeasible, then the phase II feasibility study which considers safety problems will be postponed until phase I studies on potentially more promising waste-matrix-container systems have been completed. If the results of the phase I study indicate this waste-matrix-container combination to be potentially feasible, then the more detailed phase II feasibility study will be conducted. Phase II studies include design for in-Shuttle cooling, emergency and accident conditions, and considers Shuttle safety environment, abort, reentry, impact, and heating after an impact-burial. The following sections describe the design criteria, procedure, and assumptions for the phase I analysis.

4.1 Design Criteria

For phase I studies, three criteria are considered: external radiation dose rate levels, matrix material temperature limits, and Shuttle payload weight limits. In the double Shuttle launch, where the payload and Tug are placed in orbit on separate launches, the maximum payload is determined not by the Shuttle capability but by the Tug's capability to transfer the payload from low Earth orbit to the candidate destination.

Radiation dose rate levels. - The dose rate level considered in this phase of the study is based on acceptable levels to the general public after an accident. This dose constraint was assumed to be 1 rem/hr at one meter from the surface of the sphere. However, the effect of dose rates up to 100 rem/hr was also determined.

Temperature limits. - The maximum temperature was selected based on the criteria that materials do not melt. Since the matrix material selected for the actinides consisted of a combination of lithium hydride

and aluminum which have melting points near 930 K (1200° F), a maximum allowable operating temperature 70 K below the melting points was selected, namely 860 K (1090° F).

Shuttle payload limits for Earth escape. -

		kg	lb
Single shuttle launch	Payload	7 730	17 000
	Structure on payload	227	500
	Structure on shuttle	1 363	3 000
	Tug	20 200	44 500
	Total	29 520	65 000
Two shuttle launch			
Shuttle 1	Tug	26 800	59 000
	Structure in shuttle	1 363	3 000
	Total	28 163	62 000
Shuttle 2 (with dog-leg capability)	Payload	12 726	28 000
	Structure on payload	454	1 000
	Structure in shuttle	1 363	3 000
	Total	14 543	32 000

4.2 Procedure and Assumptions for Containment System Design

The steps for the design of a container and shield which meets the dose rate, the normal operational temperature and the payload criteria are listed below. These steps differ from those used in reference 3 for the all-fission-products-mix primarily because of the different container shape (spherical for actinide and cylindrical for fission products).

(1) Select a representative amount of actinides plus fission products (total 364 kg (800 lb))

(2) Mix with several amounts of matrix material and determine diameter of each sphere of waste/matrix material

(3) Determine thermal conductivity for each mixture

(4) Calculate the radiation and thermal production and transport characteristics for each mixture

(5) Calculate gamma and neutron shielding required using minimum weight as an optimization criteria

(6) Add a 2.54 centimeter (1-in.) thick stainless steel vessel for containment

(7) Calculate the surface temperature when deployed in space assuming radiation to space and a surface emissivity of 0.8

(8) Calculate the temperature distribution and obtain the peak temperature at the center of each mixture. (Assumed no temperature drop across interfaces)

(9) Select the minimum amount of matrix material that does not result in the central matrix temperature exceeding the maximum allowable.

(10) Vary actinide mass ratio downward keeping the ratio of actinides to matrix constant (from (9) determine new shielding thicknesses for each mass ratio that maintain the assigned external dose rate

(11) Determine new packaging weight ratios (i.e., total package weight per unit mass of actinides) using results of (10)

(12) Select the packaging weight ratio that results in a package weight equal to the maximum payload for each destination

(13) Determine the temperature profile for the new packages to make sure the central matrix temperature has not exceeded the limit. If it does, divide the package until the central temperature is at or below the maximum.

4.3 Procedures and Assumptions for Calculation of Space Transport Cost

The cost of space disposal of radioactive wastes can be divided into several categories.

(1) Temporary storage on Earth

(2) Separation, concentration, and preparation of wastes in matrix materials

(3) Design and fabrication of the space disposal container system and assembly of wastes and matrix material into the container

(4) Shipment of wastes to the launch site

(5) Space transportation cost

This report is concerned with only one of these costs - the space transportation cost. The space transportation costs begin when the payload is delivered to the launch site. The major space transportation costs is assumed to end when the payload gets to its destination. Additional monitoring costs, as could be required for some of the disposal destinations are neglected.

All of the above costs will have to be determined before a complete economic analysis can be made. The purpose of the present analysis is to determine the relation of only the space transportation cost to the cost of generating electricity. Specifically, the space transportation cost will be compared with the bus-bar cost of electricity which is assumed to be 8 mils per kilowatt-hour and to the consumer cost which is assumed to be 24 mils per kilowatt-hour.

The factors that affect the space transport cost to the electric power consumer are:

(1) Launch cost including the cost of the shuttle and tug

(2) Destination and gross payload

(3) Ratio of radioactive waste to gross payload weights

(4) Radioactive waste Earth storage time

(5) Potential interest earned on funds set aside for space disposal

The first four are factors which determine the cost at launch time in 1972 dollars. All five factors determine the charge that the consumer must pay at the time he consumes the electricity, which will be at least 10 years before launch and may be 20, 30, or more years before launch.

The steps for the economic analysis are:

(1) Determine the gross payload for the Earth escape destination which is a base point in this study. Gross payload is defined as the weight of the waste container system delivered to the destination and includes all structures and auxiliary systems fixed to the container

(2) Determine the net waste container payload by subtracting the weights of the structures and auxiliary systems fixed to the waste container from gross payload

(3) Determine the amount of fission products that can be carried in a container whose weight including the shielding, equals the net payload

(4) Determine the launch cost including shuttle and tug

(5) Determine the launch cost per kilogram of actinides transported to destination

(6) Determine the number of kilograms of actinides generated per kilowatt-hour of electrical power

(7) Determine the space transportation cost as a function of the kilowatt-hours of electricity that was originally produced when the actinides were formed, mils per kilowatt-hour

(8) Determine the discounted space transportation cost per kilowatt-hour of electricity produced, that is, determine the amount of money (mils per kilowatt-hour) that could have been put in a trust fund for space transportation. This assumes that the consumer was charged for space transportation when he used the electricity and that the money was put in a trust fund and compounded at current interest rates

(9) Compare the cost of space transportation from steps 7 and 8 to the generating cost at the bus-bar prior to distribution (approximately 8 mils/kW-hr) and to the cost to the consumer (approximately 24 mils/kW-hr)

5. RESULTS AND DISCUSSION

The Results and Discussion is divided into four sections. The first section summarizes the gross payload performance for various destination and launch vehicles. The second part describes the actinide waste package designed for normal operating conditions and discusses the effects on the design of (1) the allowable dose rate external to the container, (2) the temperature (surface and internal), and (3) the amount of actinide waste in a package. The third section relates the cost of space transportation of the waste material to the cost of producing the electricity which produced the waste material in mils per kilowatt-hour. Furthermore, it discusses how this cost can be altered by Earth storage time, interest rates, allowable dose rates and degree of fission product contamination. The final section consists of an estimate of the required number of launches per year required to dispose of the actinides produced and stored for ten years after removal from fuel elements. The amount of actinides generated is based on the projected nuclear power needs described in reference 4.

5.1 Gross Payload and Launch Vehicle Cost

The gross payload is not affected significantly by the type of radioactive waste contained in the package. Therefore, the results presented in reference 2 are applicable to both the disposal of fission product waste reported in reference 3 and the actinide waste reported herein. The following is a portion of the results described in reference 2.

Earth escape was assumed as the disposal destination and the Shuttle was selected as the launch vehicle for preliminary feasibility screening

studies. Gross payload is defined as the weight of the waste container plus all attached structures. Single and dual Shuttle operations appear to have equal feasibility and therefore both are considered. In single Shuttle operation both the waste payload and tug are carried in the same Shuttle. In dual Shuttle operation one Shuttle carries the waste payload and the other carries an expendable Tug. The following table summarizes the payload and cost data for Earth escape.

PAYLOAD AND COST DATA FOR EARTH ESCAPE

Vehicle	Gross payload weight,		Launch cost, $	Cost per pound of gross payload	
	kg	lb		$/kg	$/lb
Single shuttle with expendable tug	8 500	18 700	16.5 M	1940	881
Dual shuttle launch	13 180	29 000	27 M	2048	931

The costs per kilogram of gross payload are $1940 and $2048 and are essentially the same within the accuracy of this study. The selection of single Shuttle or dual Shuttle operation will be made at a later time and will depend on additional considerations, for example ratios of waste weight to gross payload weight (this ratio tends to increase with increasing gross payload), effect of trajectories with dog-legs (this tends to reduce the single shuttle payload), the complexity of the dual operation compared to single Shuttle operation, and other safety considerations.

For reference, table 3-1 shows the payloads and costs for some of the shuttle-tug combinations and other candidate launch vehicles and destinations. The candidate destinations considered, in order of decreasing ΔV requirement (lowest payload), are: direct solar impact, direct solar escape, solar impact via Jupiter, solar escape via Jupiter, solar orbit, solar orbit via Venus, solar orbit via Mars, high Earth orbit, Earth escape, and low Earth orbit. The candidate expendable vehicles starting with the highest payload capability in a high Earth orbit were: Saturn V/Centaur, Saturn V, and Titan III E/Centaur. Representative destinations and vehicles are listed in table 3-1. None of the launch vehicles listed could deliver a payload for direct solar impact.

When selecting the candidate destination and launch vehicle, other factors besides payload and launch cost must be considered. For example, the Jupiter, Venus, and Mars fly-by missions require less ΔV but more accurate instrumentation and control than the more direct missions, and also require propulsion burns many months after leaving the Shuttle orbit. In addition, Jupiter, Venus, and Mars must be in the proper positions for

launch and this occurs for only about one month every 12, 19, and 25 months, respectively. Thus the fly-by missions would require all the launches for the 12- to 25-month period be made during an approximately one month launch window. This would require many launches per day with a launch window of about 1/2 hour per day (ref. 2).

Earth escape, Earth orbit, and solar orbit result in the higher payloads per vehicle but each has drawbacks that must be investigated. In the case of Earth escape, the possibility of re-encounter with the Earth at some future time would have to be negligibly small for several hundred thousand years due to the long-life of the actinide waste materials. In the case of Earth orbit the possibility of interference with other space activities must be studied and made acceptable; the problems of very long term storage in orbit must be determined and analyzed. Solar orbit reduced these problems but requires additional burns about six months later in the mission. Earth orbit also requires additional burns but these occur only hours or several days later in the mission. Solar system escape would eliminate some of these problems but would be more costly and requires additional staging because of the higher Delta-V needed. These types of considerations are discussed by Ramler, Thompson, and Stevenson in reference 2. More detailed analysis of this type, integrated with safety and economic analyses are required before a destination can be firmly selected.

5.2 Waste Payload Design

The characteristics of the waste, matrix, shielding materials and containers are described in section 2 - tables 2-1, 2-2, and 2-3; and figures 2-1 and 2-2. The design procedures and assumptions for the container and shield are described in Section 4.1 and 4.2. The results of the parametric analysis of these designs is presented in figures 5-1 through 5-3 and is discussed below.

There are four main caregories of design criteria:

(1) Radiation dose rates of 1 to 100 rem per hour at 1 meter from the surface of the shield

(2) Matrix material containing the actinides and the fission products shall be 70 K less than the melting point of controlling material (in this case lithium hydride - 860 K)

(3) Gross payload weight: 8500 kilograms (18 700 lb) for single shuttle and 13 180 kilograms (29 000 lb) for dual shuttle operation.

(4) Fission product contamination of the actinides of 0.1 and 1 percent

An additional design criterion, Earth storage time, does not appreciably alter the design; however, it can affect the initial cost to the consumer as would any assigned interest rate.

The dependent parameters are:

(1) The diameter of the mixture of waste and matrix material

(2) The diameter of the outer containment vessel

(3) The containment vessel surface temperature

(4) The thermal power of the actinides plus fission products

Diameter of the matrix material. - The actinide oxides including the small percentages of fission products can be diluted with matrix material over a range of dilutions. For this report a constant quantity of actinides was assumed to be diluted with various amounts of matrix material (LiH, Cu, Al). Decreasing the amount of matrix material decreases the diameter of the matrix with the actinides which decreases the radiation self shielding and increases the shielding required around the matrix. The diameter of a waste-matrix mixture containing 364 kilograms (800 lb) of actinide oxides plus fission products was varied from 1.22 meters (4.0 ft) down to 0.84 meter (2.75 ft). As the diameter was decreased for a constant heat source the central matrix temperature increased as shown in figure 5-1. This is due in part to the increase in heat generation per unit volume coupled with a decrease in surface area of the actinide waste. The other factor is that the decrease in matrix material (which is primarily lithium hydride) requires an increase in external lithium hydride thickness for neutron shielding. The temperature difference across the lithium hydride is greater due to the increased thickness and higher heat flux. As can be seen in figure 5-1, the matrix diameter of 0.81 meter (32 in.) slightly exceeds the limiting temperature for 0.1 percent fission product contamination. The 1 percent fission product contamination would allow a smaller diameter (0.79 m) without exceeding the center temperature limit.

Outer diameter and temperature of the containment vessel. - The outer diameter of the containment vessel depends on the matrix diameter, and the amount of shielding needed to reduce the dose rate to the desired level. A dose level of 1 rem/hr 1 meter from the surface was assumed. Figure 5-2 shows the relation between the matrix diameter and the outer containment diameter for a constant amount of actinides.

Using these outer diameters, the thicknesses for each layer, and the heat source from the waste material; both the surface temperature and a temperature profile can be determined. It is assumed that the removal of heat is solely through radiation into space. An emissivity of 0.8 is assumed for the radiating surface. The surface temperatures for the cases

with a constant amount of actinides are shown in figure 5-3. For the limiting central matrix temperature case, the outer surface temperature was 583 K (1050° R).

The weights of the spherical packages containing 384 kilograms of actinides are 4434 kilograms for the case of 0.1 percent fission products and 5411 kilograms for the 1.0 percent case. These weights include the containment vessel but not the re-entry shells.

The dominant shield material in terms of temperature effect is lithium hydride; however, the dominant shield material in terms of weight is tungsten. For the 0.1 percent fission product contamination case, the tungsten weight is two-thirds of that needed for the 1 percent fission product contamination case.

Both cases resulted in weights less than the allowable weight for the single shuttle launch with an Earth escape mission. The ratio of total package weight to actinide weight shown in figure 5.4 is decreasing with increasing diameter. For this figure the minimum volume ratio of matrix to actinide, based on central matrix temperature, was selected and shielding calculations performed over a range of actinide mass. From these, total package weight ratios were obtained. For a given payload the amount of actinides in the package can be obtained. This was done for each payload limit. For each case, central temperature was determined. If the temperature of the matrix exceeded the allowable temperature, the payload was divided into more than one package using the proper packaging ratio. The package characteristics assuming a payload capability of 8530 kilograms (18 700 lb) (Earth escape) and a dose rate of 1 rem/hour at 1 meter from the surface are presented in table 5-1. For the 0.1 percent fission products the waste package was subdivided into two packages. The total weight of actinides (less fission products) was 620 kilograms (1365 lb). The 1-percent fission product case was slightly high in temperature for the matrix (865 K). The weight of actinides (less fission products) was 416 kilograms (916 lb).

Effect of dose rate on shield thickness and shield weight. - The results presented are, for the most part, based on providing shielding to reduce the dose rate at 1 meter from the container surface to 1 rem/hour. If higher dose rates are allowable the effect will be to increase the ratio of actinides to total package weight. The change in shielding thickness for both the gamma shield (tungsten) and the neutron shield (lithium hydride) with dose rate are shown in figure 5-5. As the allowable dose rate increases, less shielding will be required and the weight, especially of the tungsten shield, can be reduced. A 50 percent reduction in shield weight can be obtained with a factor of 10 increase in dose rate from 1 to 10 rem/hour. This would not allow an equal increase in actinides in a package because of the temperature limits. Removal of all tungsten and lithium hydride shielding increases the dose rate to approximately 450 rem/hour at 1 meter from the outer surface.

5.3 Space Transportation Cost

The factors that affect the space transportation cost and the procedures and assumptions for calculating that cost are described in Section 4.3. The purpose of the analysis is to estimate the space transportation cost to the electric power consumer and to compare this cost to the electric cost, which at present is approximately 8 mils per kilowatt-hour (Cleveland, Ohio area) at the bus-bar and 24 mils per kilowatt-hour average to the residential consumer.

The effect on the space transportation cost of each of the main parameters in the cost analysis has been determined. The parameters, the baseline values for the parameters, and range of variation of the parameters are listed in table 5-2. The effect of a parameter is determined by varying the parameter, keeping the other parameters fixed at the baseline value. The results are presented in table 5-3 and the effect of the following parameters on the space transportation cost are discussed below:

(1) Destination
(2) Dose rate
(3) Fission product contamination of actinides
(4) Earth storage time
(5) Space disposal fund interest rate

Effect of destination on cost. - The gross payload and the cost per pound of gross payload are presented in table 3-1 for the candidate destinations and the required vehicles. Gross payload is defined as the weight of the waste, container system and structure permanently attached to it. The ratio of radioactive waste weight to gross payload depends on the character of the waste and the design of the container. The cost in dollars per kilogram of gross payload for the candidate destinations is listed below. This represents the minimum cost since the analysis considered only normal operating conditions. Consideration of emergency and accident provisions would tend to increase this cost.

Earth escape, \$/kg.	1765
High Earth orbit, \$/kg.	1765
Solar orbit, \$/kg	1965
Solar escape via Jupiter, \$/kg.	4050
Solar impact via Jupiter, \$/kg.	4830
Direct solar escape, \$/kg	8720
Direct solar impact, \$/kg	Cannot be done with existing vehicles

The effect of the destination on space transportation cost in terms of mils per kilowatt-hour electric is presented in table 5-3 for two destinations. From table 5-3 the space transportation costs for Earth escape and solar escape are 0.171, and 0.746 mils per kilowatt-hour, respectively

for actinides with 1 percent fission products and a dose rate of 1 rem/hour.

Effect of dose rate. - The effect on space transportation cost of varying the external dose rate from 1 to 10 to 100 rem/hour was determined for the Earth escape destination and is shown in table 5-3. These costs in mils per kilowatt hour are 0.171, 0.114, and 0.079, respectively. The cost per pound of waste delivered for the 10 rem/hour dose is 67 percent of the 1 rem/hour cost. The cost for the 100 rem/hour dose is 45 percent of the 1 rem/hour cost.

Effect of fission product contamination. - Decreasing the amount of fission products remaining in the waste from 1 to 0.1 percent results in a decrease in shielding and therefore an increase in actinide waste in the gross payload (table 5-3). For a dose rate of 1 rem/hour at 1 meter from the surface reducing the fission product contamination from 1 percent to 0.1 percent reduces the cost for space transportation from 0.171 to 0.114 mils/kilowatt-hour or a reduction in cost of 33 percent.

Effect of interest rate. - In all cases considered the radioactive waste is stored for at least 10 years before reprocessing for disposal or permanent storage. This is true independent of whether the waste is to be reprocessed for Earth or space disposal. However, the electric customer pays for both the storage and reprocessing costs at the time he uses the electricity. If the plan were to dispose of the waste in space, then the electric consumer would also be charged for the space disposal at the time he used the electricity. The charge to the consumer depends on the interest rate, the storage time and the launch cost per pound of waste at the time of disposal. Assuming 10 years Earth storage before space disposal the charge to the consumer for space transportation is 0.171, 0.105, 0.086, and 0.066 mils per kilowatt-hour for interest rates of 0, 5, 7, and 10 percent, respectively.

Effect of Earth storage time. - As indicated above the cost to the electric consumer for space transportation decreases as the storage time increases, primarily due to the interest accumulated on the disposal fund. At a 5 percent effective interest rate the amount in the disposal fund will double about every 15 years. Thus, assuming a 5 percent effective interest rate, the charge to the electric consumer for space transportation will be 0.086, 0.043, and 0.022 mil per kilowatt-hour for Earth storages times of 15, 30, and 45 years, respectively. An additional charge estimated at 0.01 mil per kilowatt-hour is required to pay for the Earth storage prior to launch (ref. 1).

5.4 Number of Shuttle Launches per Year

The number of Shuttle launches per year is dependent on two factors: the quantity of actinides produced from the generation of electricity

through nuclear reactors and the quantity that could be carried in a Shuttle launch. The estimated weight of actinides and fission products produced to the year 2020 is shown in figure 5-6. The weight of actinides is approximately 1/20 that of the fission products.

The amount that can be carried per Shuttle flight is a function of the following factors:

(1) Destination
(2) Allowable dose rate
(3) Percent of fission products in actinide waste

Table 5-1 shows the quantity of actinide waste per package assuming an Earth Escape mission with a total payload of 8500 kilograms (18 700 lb). This data coupled with the data from figure 5-6 yields the number of Shuttle flights per year after a 10 year hold as shown in figure 5-7. The curves indicate that only five launches to Earth escape velocity are needed in 1985 for material produced in 1975. By the year 2000, this launch frequency would increase to 36 if 1 percent of the fission products remain in the actinide waste or 25 if 0.1 percent fission products remain in the waste. For comparison purposes, if the destination is solar escape, then the launch frequency increases due to both a smaller total package weight 3270 kilograms (7200 lb) and an additional Shuttle launch for the extra tug required for propulsion. In 1985 it would require about 25 launches for 1 percent fission products, and this requirement would increase to over 165 launches by the year 2000. With only 0.1 percent fission product contamination the launch frequency would be about 15 and 110 for the same years. If the allowable dose rate were increased by 10 times the launch rate would decrease by 35 percent

Since the cost is comparable to Earth storage (0.03 to 0.045 mil/kW-hr, ref. 1), the half lives are very long (thousands of years) and the launch frequencies are reasonable, it is recommended that a more detailed study be conducted which will design the package considering the safety aspects of launch and flight.

6. SUMMARY OF RESULTS

The radioactive waste considered in this preliminary feasibility study of extraterrestrial disposal of radioactive wastes was the actinides after separation from the mixture of radioactive wastes in spent fuel elements. Two levels of residual fission products, 1 and 0.1 percent, were assumed to be contained in the actinide waste. For this study the wastes in the form of oxides were formed into small spheres (approximately 0.318 cm in diameter), coated with tungsten (0.0127 cm) and moly disulfide (0.0025 cm) for oxidation protection and mixed into a metal matrix

(aluminum and copper) for thermal conduction, along with some lithium hydride for neutron moderation and control. This waste containing matrix was then packaged in shielding material (tungsten and lithium hydride layers) and contained in a stainless steel containment spherical shell (2.54 cm). The shielding was optimized to minimize weight for a range of dose rate from 1 to 100 rem/hour at 1 meter from the surface of the outer shell.

The purpose of this preliminary study was to determine whether or not space disposal could be practical from the standpoint of launch frequency and cost of the space transportation. This first phase of the study presented in this report does not take into consideration the weight penalties due to systems necessary to protect the package during accidents. The results, therefore, represent the minimum cost and maximum quantity of actinide waste per payload. This study is intended to be primarily a screening study to determine if space disposal of actinide wastes should be looked at in greater detail. The Shuttle was selected as the most promising launch vehicle in a previous study (ref. 4) in which the Shuttle was shown to result in the lowest launch cost per pound of waste. The destinations considered were Earth escape and solar escape. The following results were obtained:

1. The space disposal of actinides appears sufficiently promising to warrant a more detailed study that includes analysis and design for the probable accident conditions.

2. Based on a container designed for normal operating conditions the space transportation cost to place radioactive actinides containing 1 percent fission products in a high Earth orbit or in an Earth escape solar orbit is 0.2 mils per kilowatt-hour, about 1 percent of the present average cost to the consumer for electricity.

3. Decreasing the fission product contamination in the actinides from 1 to 0.1 percent reduces the cost for space transportation by 33 percent.

4. Increasing the allowable does rate at 1 meter from the surface a factor of 10 (1 to 10 rem/hr) reduces the weight of the necessary shielding by 50 percent and could result in up to 50 percent increase in actinides per package. Removal of all shielding increases the dose rate to approximately 450 rem/hour.

5. Frequency of Shuttle launches in 1985 would be approximately 3 to 5 per year for a high Earth orbit or Earth escape with actinides and 0.1 to 1 percent of the fission products generated in 1975, and 15 to 24 for solar escape.

6. Shuttle launch frequency in the year 2000 would be 25 to 36 for

high Earth orbit or Earth escape and 110 to 165 for solar escape for actinides with 0.1 and 1 percent fission products, respectively.

7. Assuming the electric consumer is charged for space disposal at the time the electricity was used and that the money is put in escrow at an interest rate of 5 percent per annum permits a reduction in charge to the consumer of 50 percent for every 15 years of Earth storage prior to transporting it to space.

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TABLE 2-1. - HALF-LIVES AND FRACTIONS OF MAIN ACTINIDE ISOTOPES IN RADIOACTIVE ACTINIDE WASTE FROM LWR's[a] AND LMFBR's[b] AFTER 33 000 MW-DAY (th) (REF. 4)

LWR		
Isotope	Half-life, yr	Relative fraction
Neptunium - 237	2×10^6	0.78
Plutonium - 239	2.4×10^4	.03
Plutonium - 240	6760	.02
Americium - 241	458	.05
Americium - 243	7650	.09
Curium - 244	18	.02
LMFBR		
Isotope	Half-life, yr	Relative fraction
Neptunium - 237	2×10^6	0.10
Plutonium - 238	89	.01
Plutonium - 239	2.4×10^4	.21
Plutonium - 240	6760	.08
Plutonium - 241	13	.01
Plutonium - 242	3.8×10^5	.01
Americium - 241	458	.37
Americium - 243	7650	.19
Curium - 244	18	.01

[a]LWR ≡ Light Water Reactors.

[b]LMFBR ≡ Liquid Metal Fast Breeder Reactors.

TABLE 2-2. - YIELD OF RADIOACTIVE ACTINIDES FROM TYPICAL NUCLEAR POWER REACTORS

	LWR	LMFBR
Power per metric ton of reactor fuel	30 MW(th)/MT	58 MW(th)/MT
Thermal energy per metric ton of reactor fuel	33 000 MW-days/MT	33 000 MW-day/MT
Efficiency, percent	33	40
Electric energy per metric ton of reactor fuel	10 900 MW(e)-days/MT	13 200 MW(e)-days/MT
Actinide mass[a] in waste material from processing metric ton of spent fuel	5760 g/MT	5740 g/MT
Percent uranium isotopes	82.9	76.6
In actinide waste:		
Percent plutonium isotopes	0.77	7.5
Percent thorium isotopes	Neg.	Neg.
Percent Americium isotopes	2.48	13.1
Percent protactinium isotopes	Neg.	Neg.
Percent curium isotopes	0.64	0.6
Percent neptunium isotopes	13.2	2.2
Actinide (less uranium) produced per kilowatt-hour (electrical, g/KW-hr	0.377×10^{-5} g/KW-hr(e)	0.424×10^{-5} g/kW-hr(e)

[a]Ref. 4 - ORNL-4451 - Siting of Fuel Reprocessing Plants and Waste Management Facilities, July 1970 table 3.19 and table 3.43.

TABLE 2-3 - THERMAL AND RADIATIVE CHARACTERISTICS OF THE ACTINIDES REMAINING IN WASTE GENERATED FROM REPROCESSING OF SPENT LMFBR - REFERENCE OXIDE (AI-LMFBR)

[Power = 58.2 MW(th)/MT, burnup = 32 977 MWD(th)/MT, 10 year storage.]

	Thermal power, W/g	Radiative power, curies/g
Actinides	0.0176	0.864
Actinides less uranium isotopes	.0748	3.67
Actinides less uranium isotopes plus 0.1 percent fission products	.0737	3.81
Actinides less uranium isotopes plus 1.0 percent fission products	.0654	4.78

TABLE 3-1. - CANDIDATE LAUNCH VEHICLES, DESTINATIONS, TOTAL COSTS, COSTS PER KILOGRAM OF PAYLOAD

Candidate launch vehicle and tug combinations	Launch, cost	Destinations							
		Earth orbit or Earth escape		Direct solar escape		Solar impact via Jupiter		Solar escape via Jupiter	
		Payload, wt (kg)	Cost per kilogram $/kg	Payload, wt (kg)	Cost per kilogram $/kg	Payload, wt (kg)	Cost per kilogram $/kg	Payload, wt (kg)	Cost per kilogram $/kg
Shuttle (1) and reusable tug (1)	12 M	4680	2573	0	∞	0		0	
Shuttles (2) and reusable tug (1)	22.5 M	6140	3665	0	∞	0		0	
Shuttles (2) and reusable tug (2)	24 M	12 050	1990	0	∞	0		0	
Shuttle (1) and expendable tug (1)	16.5 M	8500	1940	1045	15 600	2410	6840	3180	5190
Shuttle (2) and reusable tug (1) and expendable tug (1)	28.5 M	16 150	1765	3270	8720	5900	4830	7040	4050
Saturn V/Centaur	155 M	34 600	4480	7050	22 000	11 000	14 100	13 650	11 380
Titan III E/Centaur	19 M	3815	4980	0		0		680	17 900

TABLE 5-1. - PACKAGE CHARACTERISTICS OF ACTINIDES WITH FISSION PRODUCTS FOR EARTH ESCAPE MISSION DOSE RATE OF 1 REM/HR AT 1 METER FROM SURFACE

	0.1 Percent fission product	1.0 Percent fission product
Number of packages per shuttle	2	1
Weight of waste (actinide oxides + fission product), lb	347	571
Weight of actinides, kg	310	416
Thermal power in waste, kW	23.1	33.6
Diameter of waste matrix, cm	81.0	95.4
Thickness of tungsten, cm	3.66	6.25
Thickness of LiH, cm	12.06	14.0
Outside diameter of containment shell, cm	118.0	142.0
Temperature on surface, K	576	576
Temperature at center, K	823	865
Weight per package, kg	4250	8500

TABLE 5-2. - RANGE OF PARAMETERS FOR SPACE TRANSPORTATION COST ANALYSIS

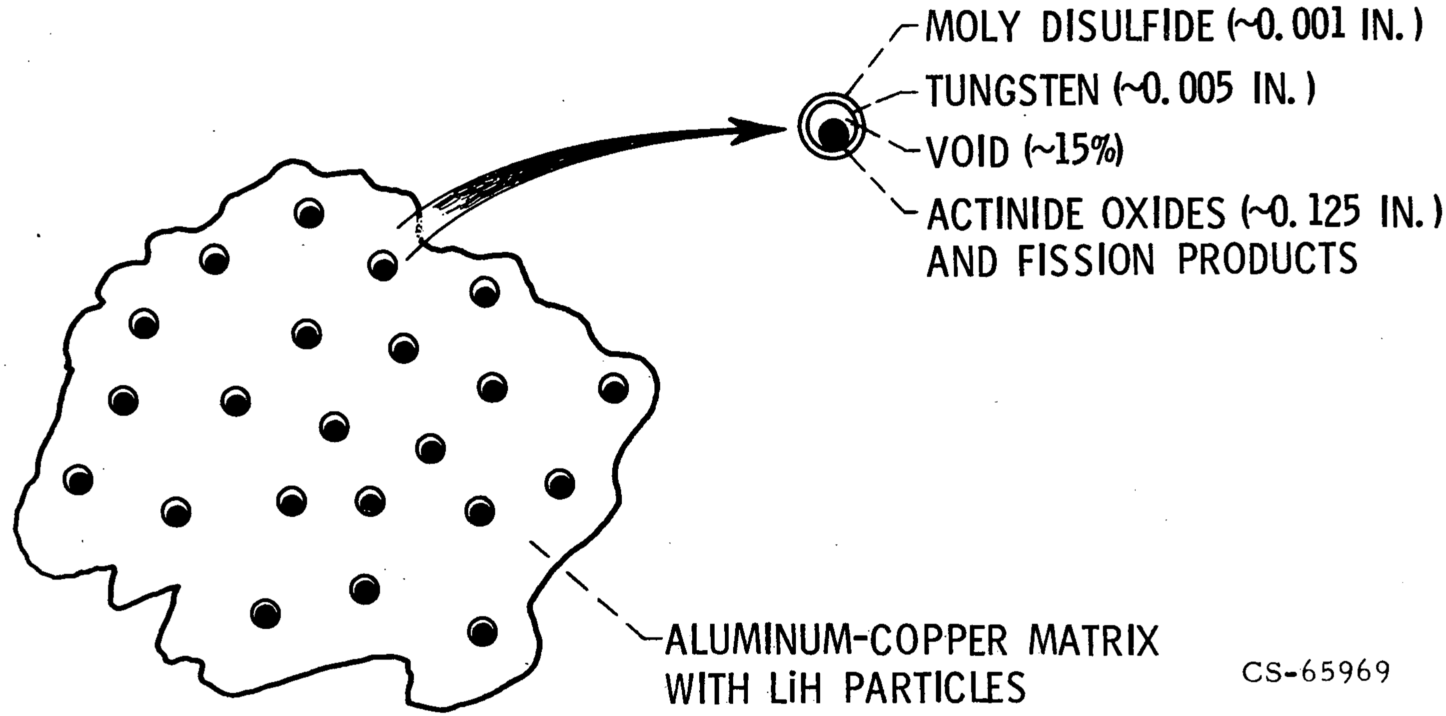
Parameter	Baseline value	Range
Destination and gross payload		
Single shuttle	Earth escape (8500 kg)	
Dual shuttle	Earth escape (13 180 kg)	Solar escape (3270 kg)
Dose rate at 1 meter from container surface	1 rem/hr	10 rem/hr and 100 rem/hr
Launch cost		
Single shuttle	16.5 Million Dollars	No range
Dual shuttle	27 Million Dollars	
Earth storage time	10 years	20 years
Interest on space disposal fund	0 percent	0 to 10 percent
Fission product contamination (percentage of atoms in waste from processing spent fuel)	1.0 percent	0.1 percent

TABLE 5-3. - RESULTS OF PARAMETRIC STUDY ON SPACE TRANSPORTATION COSTS FOR ACTINIDE DISPOSAL WITH FISSION PRODUCT CONTAMINATION

Parameter	Cost			Amount of actinides per package and number of packages per launch		Number of shuttle launches	
	Mills per kilowatt hour	Percent increase over present rate					
		Bus-bar at 8 mills	Consumer at 24 mills	kg/package	Packages/launch	1985	2000
Baseline case: Earth escape, 1 rem/hr, 1% fission product, 10 year hold with no interest rate	0.171	2.14	0.71	416	1	5	36
Destination:							
Solar escape: 1% F.P.	.746	9.32	3.11	160	1	24	165
0.1% F.P.	.502	6.38	2.09	239	1	15	110
Dose rate at 1 meter from surface							
10 rem/hr	.114	1.42	0.47	306	2	3	23
100 rem/hr	.079	0.99	0.33	440	2	2	16
Fission product contamination:							
0.1 percent	.114	1.42	0.47	310	2	3	25
Interest rate on disposal fund: (Applied for 10 yrs)							
5 percent	.105	1.31	0.44	388	1	5	36
10 percent	.066	0.82	0.27	388	1	5	36

Figure 2-1.

MODEL OF ACTINIDE WASTE & MATRIX



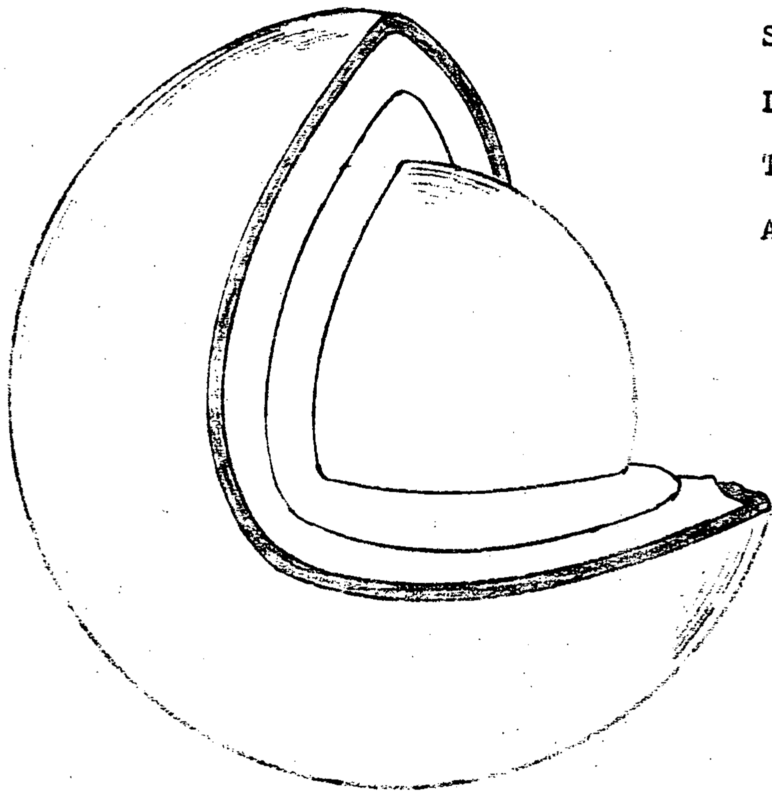
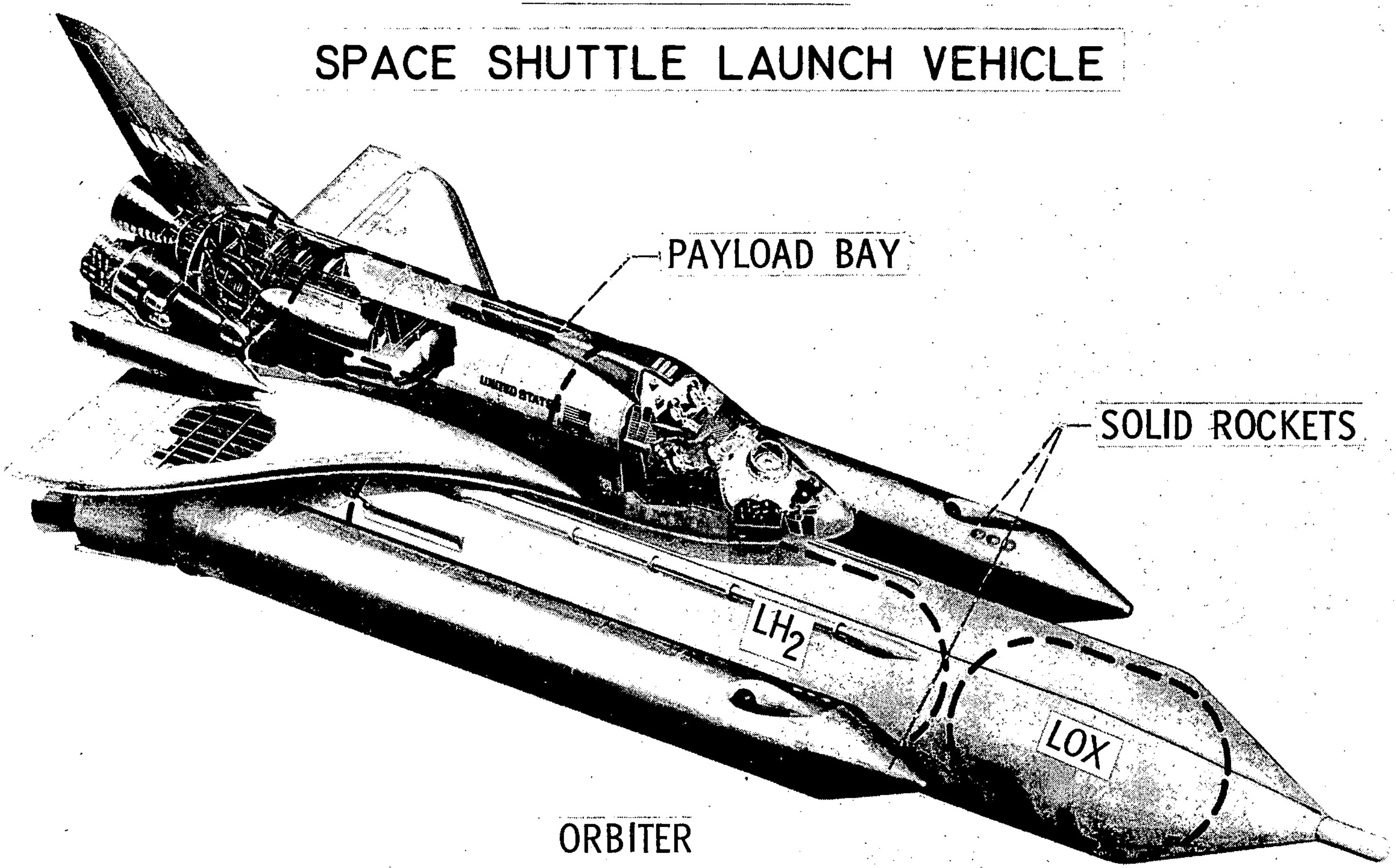


Figure 2-2 Schematic of Actinide Waste Package Without Reentry Shield

Figure 3-1.

SPACE SHUTTLE LAUNCH VEHICLE



CS-65980

Figure 3-2.

SCHEMATIC OF ORBITER & NUCLEAR WASTE PAYLOAD

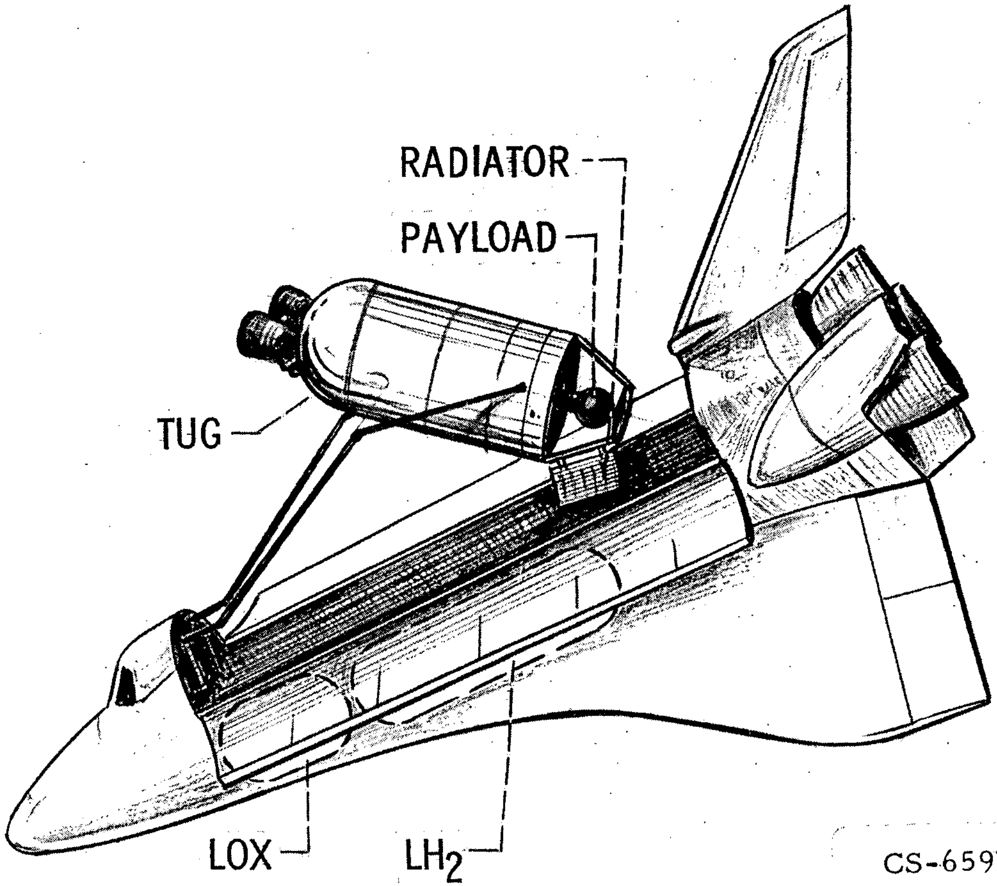


Fig. 5-1 Center Matrix Temperature vs. Matrix Diameter for Constant Source (Actinides & Fiss. Prod. 364kg) Shielded with Tungsten and Lithium Hydride to Reduce Dose Rate to 1 rem/hr at 1 meter from surface.

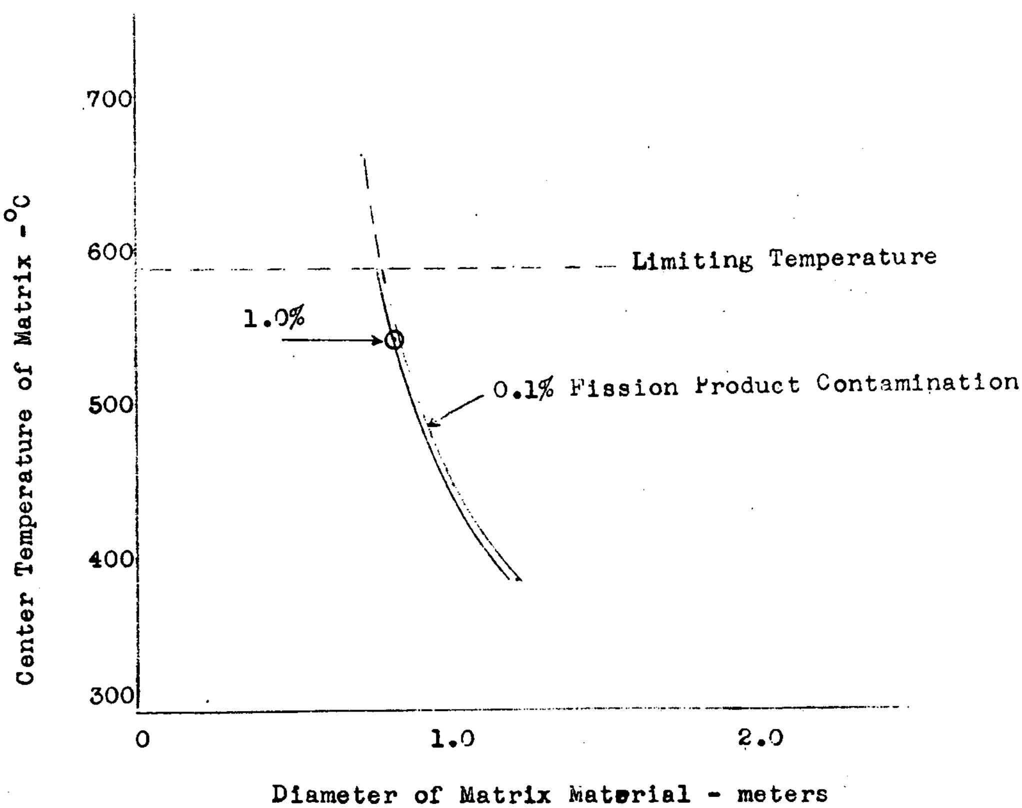


Fig. 5-2 Container Diameter vs. Matrix Diameter for Constant Source (Actinides & Fiss. Prod. 364kg) Shielded with Tungsten and Lithium Hydride to Reduce Dose Rate to 1rem/hr at 1 meter from surface.

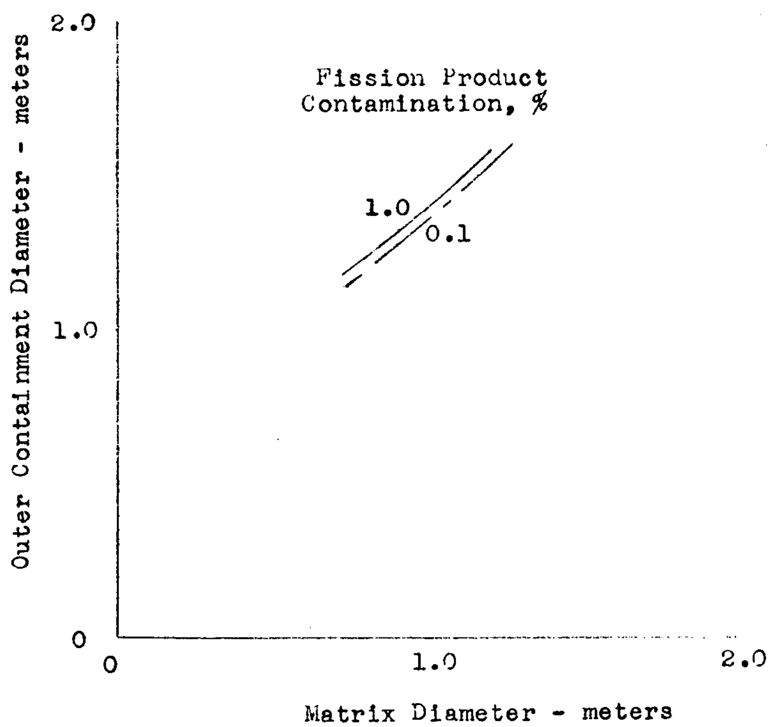


Fig. 5-3 Surface Temperature of Container Radiating to Space for Constant Source (Actinides & Fiss. Prod. 364kg) Surface Emissivity of 0.8 , Shielded with Tungsten and Lithium Hydride to a Dose Rate of 1 rem/hr 1 meter from the Surface.

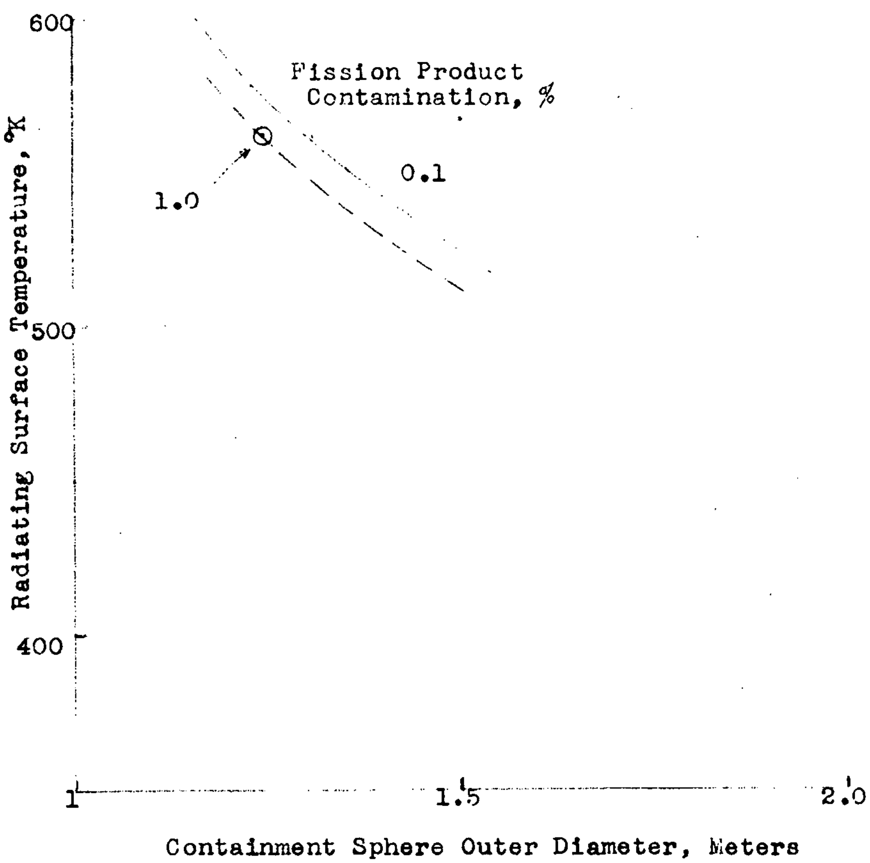
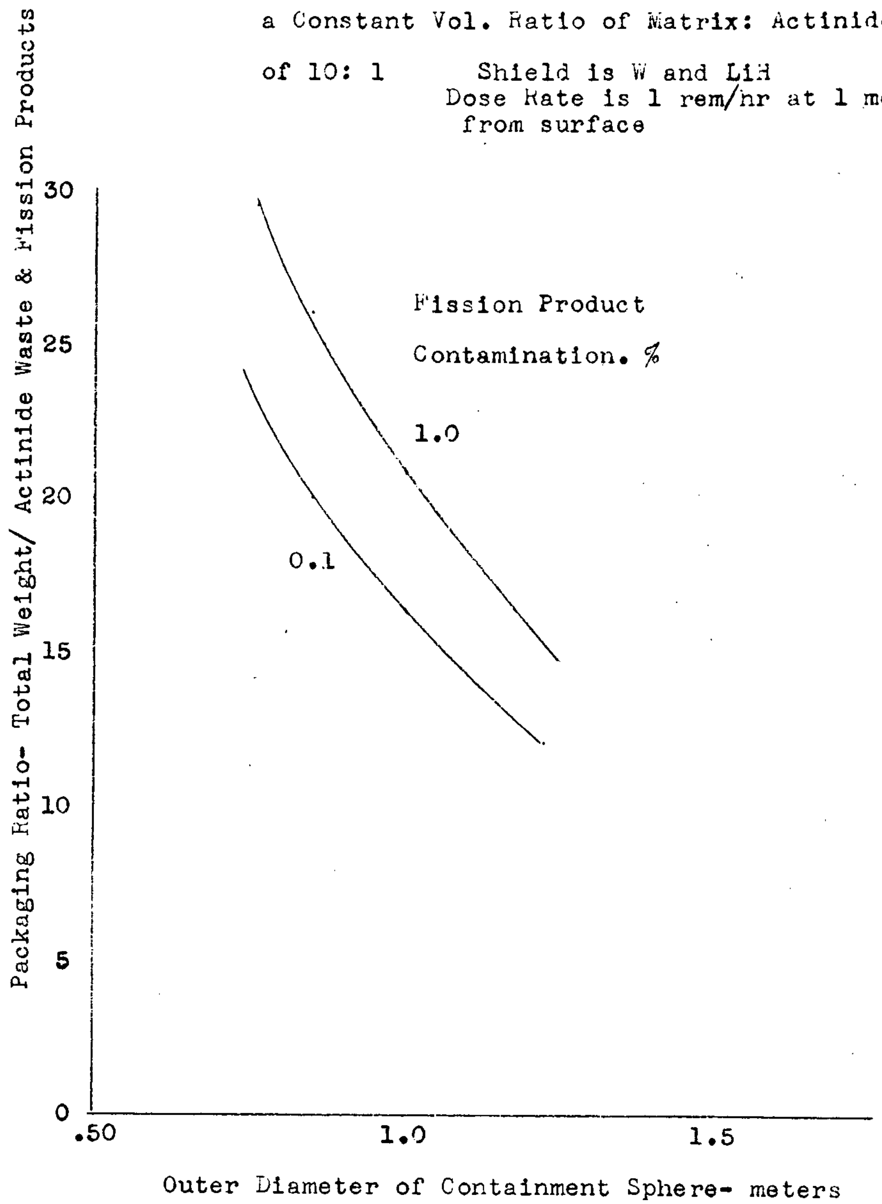


Fig. 5-4 Packaging Weight Ratio for Actinide Waste With Fission Products (0.1 and 1.0%) with a Constant Vol. Ratio of Matrix: Actinides of 10: 1 Shield is W and LiH
Dose Rate is 1 rem/hr at 1 meter from surface



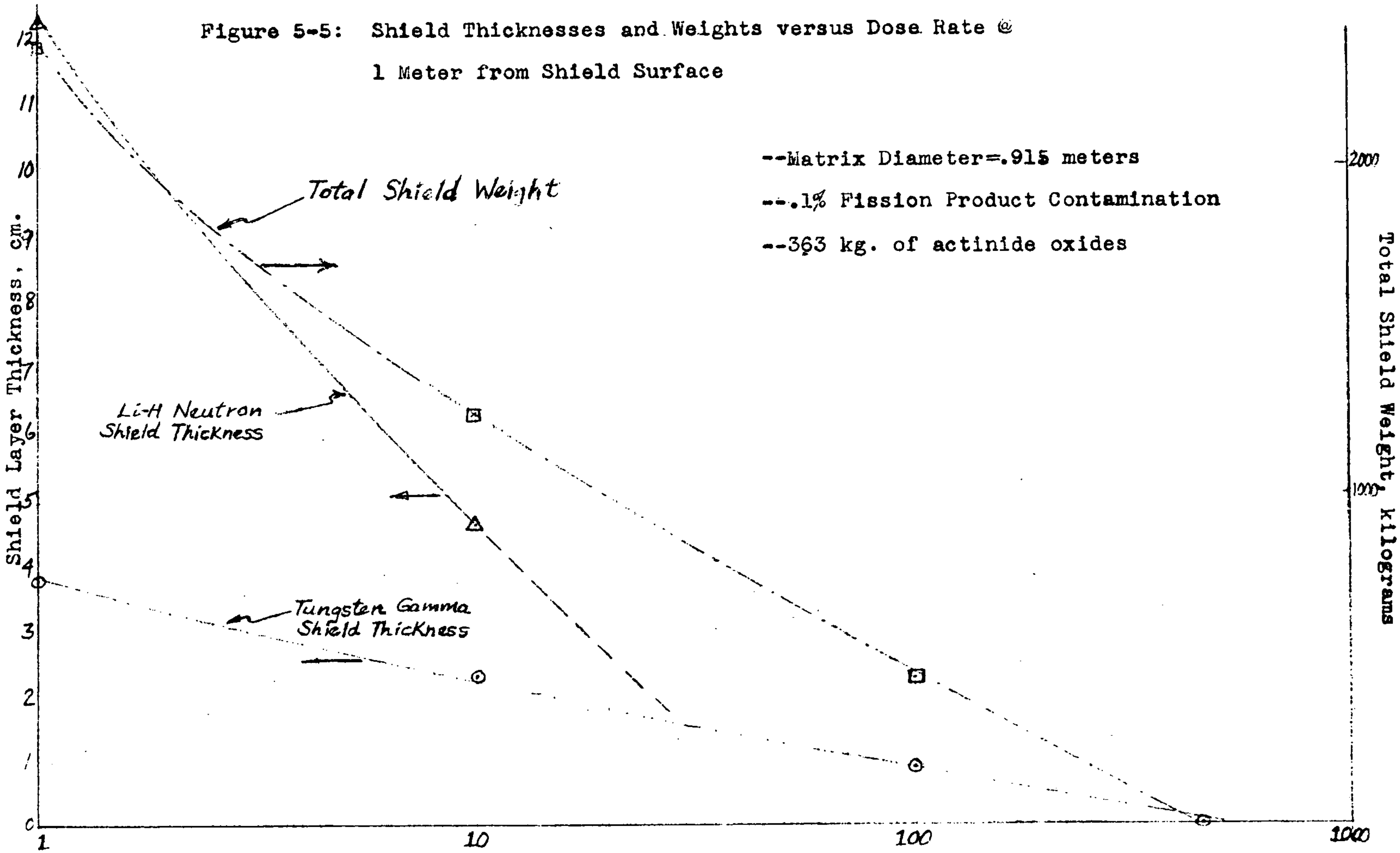


Figure 5-5: Shield Thicknesses and Weights versus Dose Rate @ 1 Meter from Shield Surface

Figure 5-6

Amount of Radioactive Waste Generated by Projected Nuclear Power Reactors (USA)

(reference 4)

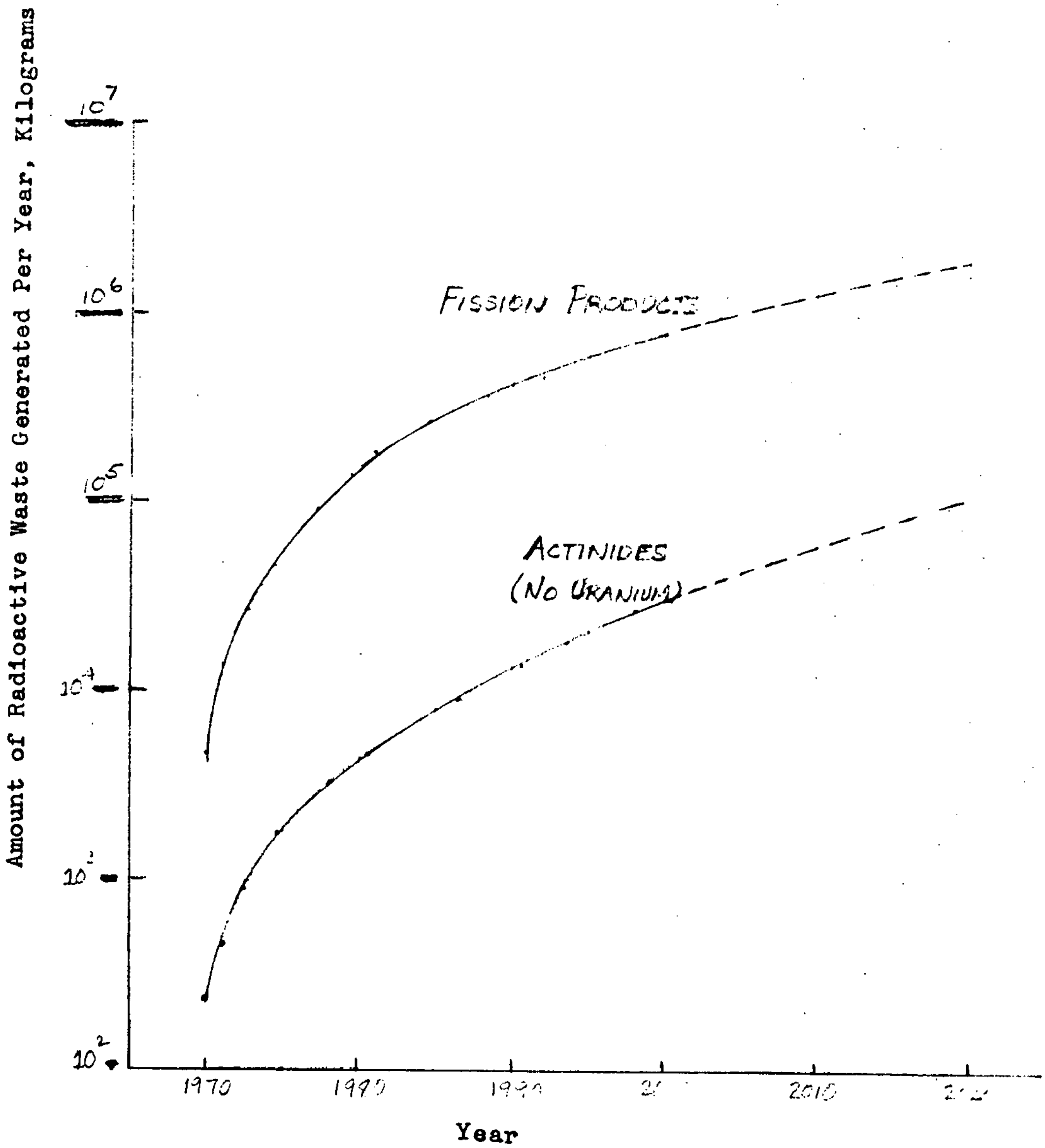


Fig. 5-7 Shuttle Launch Frequency for Space Disposal of Radioactive Actinides with Fission Product Contamination (CaseII): Ten Year Hold, Shielded for Dose Rate of 1 rem/hr at 1 meter from Surface

Packaging Ratio: 14.9 for 1.0% F.P.
12.2 for 0.1% F.P.